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Mobile Aerial Tracking and Imaging System (MATrIS) for Aeronautical Research

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ABSTRACT

A mobile, rapidly deployable ground-based system to track and image targets of aeronautical interest has been developed. Targets include reentering reusable launch vehicles as well as atmospheric and transatmospheric vehicles. The optics were designed to image targets in the visible and infrared wavelengths. To minimize acquisition cost and development time, the system uses commercially available hardware and software where possible. The conception and initial funding of this system originated with a study of ground-based imaging of global aerothermal characteristics of reusable launch vehicle configurations. During that study the National Aeronautics and Space Administration teamed with the Missile Defense Agency/Innovative Science and Technology Experimentation Facility to test techniques and analysis on two Space Shuttle flights.

NOMENCLATURE

f	f/number (focal length/aperture)
FOV	field of view, degrees
GPS	global positioning system
IR	infrared
ISAFE	Infrared Sensing Aeroheating Flight Experiment
ISTEF	Innovative Science and Technology Experimentation Facility
MATrIS	Mobile Aerial Tracking and Imaging System
MDA	Missile Defense Agency
M_∞	freestream Mach number
MVSP	motorized video surveillance platform
MWIR	mid-wave infrared
NASA	National Aeronautics and Space Administration
RA	relative aperture
RLV	reusable launch vehicle
TPS	thermal protection system
ε	emissivity
Θ'	exit angle

INTRODUCTION

A primary design driver in any reentering spacecraft is the thermal protection system (TPS). Reusable launch vehicles (RLVs) need a robust and typically reusable TPS with minimum mass in order to maximize performance and payload. Peak heating and exposure time near peak heating are key factors in TPS design. Hypersonic boundary-layer transition can cause peak heating to increase by a factor of two or more. Thus, early boundary-layer transition can have a dramatic effect on peak heating, exposure near peak heating and, ultimately, TPS design. Because of unknowns in hypersonic boundary-layer transition, added margins must be accounted for which lead to higher TPS mass and reduced RLV performance. While it is typical to attach some sensors to the windward surfaces (surfaces with highest heating), it is impractical to populate much of the surface or to have sensors on many critical areas. Furthermore, the sensors and associated equipment add weight and reduce vehicle performance. Infrared (IR) imaging has been used very successfully in the past to image and characterize boundary-layer transition and surface heating (refs. 1–3). Infrared imaging is global and nonintrusive, and in addition has the ability to show other flow features such as shock waves and some separated areas. Any flow phenomena that creates a measurable temperature change can be imaged by IR.

In an effort to develop the techniques and methods to image reentering RLVs NASA teamed with the Missile Defense Agency/Innovative Science and Technology Experimentation Facility (MDA/ISTEF) in an effort called the Infrared Sensing Aeroheating Flight Experiment (ISAFE). Using ground-based optical systems developed by MDA (formerly BMDO, the Ballistic Missile Defense Organization) two reentering Space Shuttle flights were imaged and analyzed. The results of the study (refs. 4, 5) were very favorable. The MDA equipment, however, while mobile, was difficult to rapidly deploy, had other commitments, and was costly because of its other capabilities. NASA has been designing a system that incorporates those capabilities that are needed for the reentry imaging but keeps the system very portable. The system uses commercially available components, where possible, to minimize cost and development time. In addition, NASA had been developing IR systems to image other targets of aeronautical interest, notably transition on subsonic and supersonic aircraft wings (refs. 1–3). These systems included in situ and remote airborne units. The design of this ground system would include the capability to image these and other aeronautical targets where practical.

The Mobile Aerial Tracking and Imaging System (MATrIS) is currently capable of tracking objects either optically or with global positioning system (GPS) data transmitted from the target. Infrared images can be recorded analog or digital, while simultaneously-captured visual wavelength images are recorded analog. The main optics are a multi-spectral telescope with a Cassegrain focus, 12.5-inch (31.75 cm) main mirror, 300-inch (762 cm) focal length, f/24, with a field of view (FOV) of 0.06 degrees also configured as an f/12, 150-inch (381 cm) focal length with an FOV of 0.12 degrees. This is optically equivalent to the MDA/ISTEF 12.5-inch telescope used in the initial study. The unit utilizes a shared aperture for mid-wave infrared (MWIR) and visible wavelength cameras. The gimbal is capable of azimuth velocity from < 0.1 to 100 deg/sec, elevation velocity from < 0.1 to 60 deg/sec, azimuth acceleration to 100 deg/sec^2, elevation acceleration to 60 deg/sec^2, micro-step position control, and four-microradian step resolution.

This report will present the development and design of, and the results from, the system.

BACKGROUND

This section will discuss the technical background, past experimental results, and the development of the tracking and imaging system.

Windward Reusable Launch Vehicle Aerothermal Measurements

The study of windward aerothermal characteristics of RLVs or any reentering vehicle is of vital interest to designers of these vehicles. The TPS is a major design constraint of any reentering vehicle.

Understanding the characteristics of the aeroheating and, specifically, the hypersonic boundary layer at transition can lead to more effective TPS design. Infrared thermography, which measures the thermal radiance of an object, is a useful technique to determine boundary-layer transition and surface temperature, as well as other flow phenomena. The principle of IR thermography is that all bodies with a temperature above absolute zero continuously emit, absorb, and reflect radiation in a characteristic manner. The emission intensity peaks at shorter wavelengths for higher temperatures and at longer wavelengths (for example, IR) for lower temperatures. At a given wavelength the emission intensity also typically increases with temperature. The intensity of the image of such an object also varies with other factors such as target surface emissivity (ε), path transmittance, and atmospheric radiance. With sufficient calibration, the IR intensity can be related back to an accurate surface temperature. If independent in situ surface temperature measurements are available the process is much simpler and more accurate. These in situ measurements serve as benchmarks for the rest of the image and thus, many of the aforementioned factors can be neglected. Blanchard et. al. (ref. 5) details the image-processing techniques and subsequent data analysis for both methods.

NASA/Missile Defense Agency Infrared Sensing Aeroheating Flight Experiment

An experiment using ground-based IR imagery to capture global windward surface temperatures on the Shuttle orbiter during boundary-layer transition was undertaken. The primary objective of ISAFE was to obtain hypersonic heating data in order to develop the capability to accurately determine and predict hypersonic boundary-layer transition in future vehicles. This project was a collaboration between NASA and MDA/ISTEF. ISAFE collected data on two Shuttle flights: STS-96 on June 6, 1999 (ref. 4), and STS-103 on December 27, 1999 (ref. 5). The Shuttle orbiter Discovery was the vehicle for both STS-96 and STS-103. Figure 1 shows the MDA/ISTEF Kineto Tracking Mount (KTM) which includes the 24-inch (61 cm) aperture telescope and figure 2 shows the MDA/ISTEF Small Transportable ISTEF Pedestal System (STRIPS) mount which includes the 12.5-inch (31.75 cm) aperture telescope, both used during ISAFE.

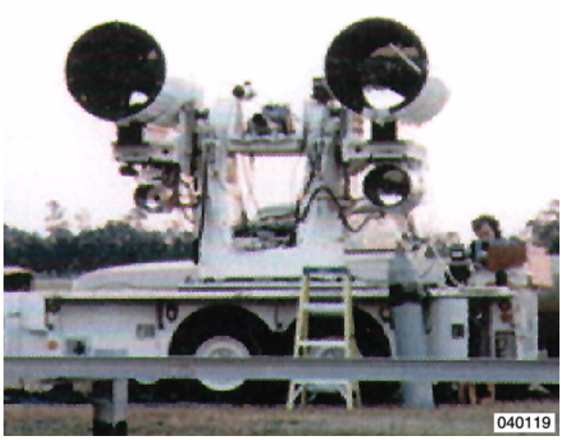

Figure 1. MDA/ISTEF KTM mount.

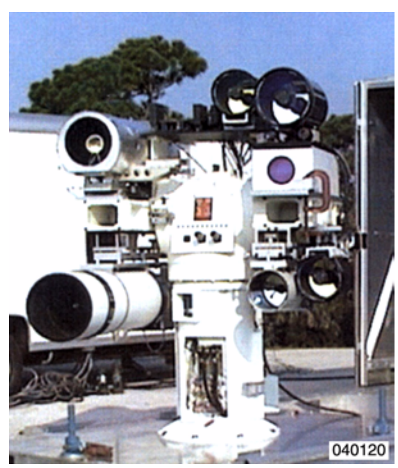

Figure 2. MDA/ISTEF STRIPS mount.

STS-96 Results

Imaging of Shuttle STS-96 was obtained on June 6, 1999 at the NASA Kennedy Space Center. The orbiter reentered on an orbit earlier than nominal and passed nearly over the acquisition site prior to entering the terminal approach area. Images were obtained using both a 24-inch (61 cm) aperture telescope system (fig. 3) and a 12.5-inch (31.75 cm) aperture system (fig. 4). It was desired to capture images with the 12-bit digital data stream from the mid-wave IR camera as well as with the 8-bit analog data stream, however, problems with the digital data recording allowed only the analog data to be recorded. The orbiter was acquired and tracked while approaching from the south but the trackers were unable to keep up with the high angular rates (at elevation angles near 90°) as the shuttle passed overhead. Orbital vehicles at high inclinations can have a vastly different ground track when reentering from a different orbit number (earlier or later than nominal). Images were obtained between Mach numbers of 1.95 (immediately after acquisition) down to approximately 1.48. The conditions recorded were much later than those for the expected transition region (M_∞ ~ 8 to 10) but proved the basic techniques. Discovery, like the other orbiters, has several thermocouples located on the windward surface that are used for diagnostic purposes after each flight. These data were available to compare and calibrate the infrared thermography data that was collected from the ground. Because of the resolution sensitivity of the IR sensor set prior to image acquisition, the hottest regions (nose and wing leading edges) are saturated. That is they are hotter than the highest temperature shown on the associated scale.

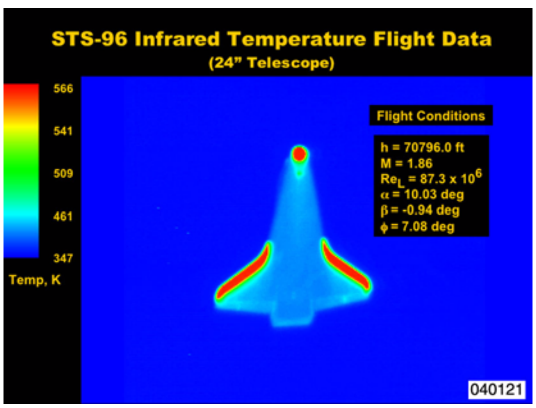

Figure 3. ISAFE STS-96 IR image with ISTEF 24-inch telescope.

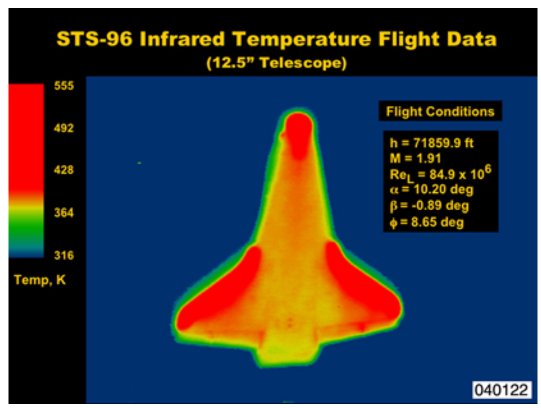

Figure 4. ISAFE STS-96 IR image with ISTEF 12.5-inch telescope.

STS-103 Results

Imaging of Shuttle STS-103 was obtained on December 27, 1999. To increase the odds of capturing the shuttle reentry given the variability of the ground track with entry orbit number, two systems were deployed on the Florida west coast. One system was deployed south at Sanibel Island and one north at Cedar Key. The northern deployment was successful in capturing the returning shuttle. Data were acquired from an initial altitude of 135,000 ft (M_∞ ~ 6) down to approximately 90,000 ft (M_∞ ~ 3). At that site the ground track was due south and the images tended to show more of the port side of the shuttle except during roll maneuvers, when the windward surface became visible. These images were obtained with a 24-inch (61 cm) diameter f/12 telescope. Figure 5 shows a single frame of the raw processed image while figure 6 shows this same image after it was processed and calibrated for resultant surface temperatures. These images complemented earlier images from STS-96 and further validated the approach and methods, but again did not capture boundary-layer transition on the windward side. The requirement of being relatively close to the ground track was also emphasized in order to be able to best characterize transition on the windward surface.

Figure 5. STS-103, raw image.

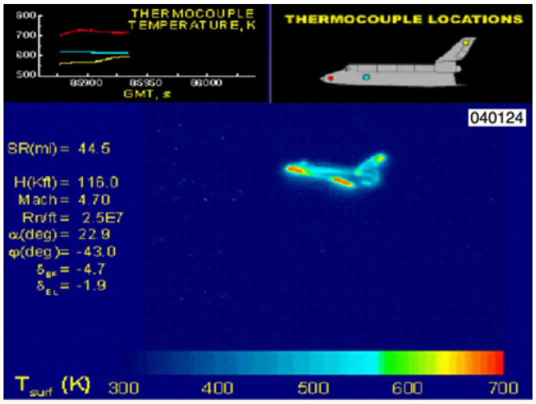

Figure 6. STS-103 reduced temperatures.

Development of the Mobile Aerial Tracking and Imaging System

The ISAFE results showed that these types of ground-based measurements were a very valuable tool to gather accurate windward global aeroheating measurements. It was, however, a time- and labor-intensive undertaking to field the MDA/ISTEF mounts, especially when multiple locations were needed to account for possible different ground tracks from different reentry orbits. Also, the MDA/ISTEF mounts were heavily utilized and significant lead time was often necessary to schedule them. Since the ISTEF mounts had significantly more capability than was needed for the ISAFE experiment, the idea emerged of developing a smaller, simpler setup that was tailored for reentry vehicle heating measurements. This would reduce the time and effort to field a system, and could result in reduced cost, possibly leading to a system that could be rapidly fielded to account for orbital variation at reentry and also one in which multiple systems could be fabricated that could be located at several strategic locations to account for reentry ground track variation. Based on the results from ISAFE the 12.5-inch (31.75 cm) aperture telescope offered good results for its size. Much larger optics (for example, 24-inch aperture) become more difficult to field and are much more expensive. A system was designed that employed as much off-the-shelf hardware as possible to minimize cost and development time.

METHODOLOGY AND APPROACH

System Design Philosophy

The design philosophy was to develop a system that was mobile, rapidly deployable, rugged, and relatively inexpensive. To that end, compromises had to be made. Commercial-off-the shelf (COTS) components and equipment previously designed for another purpose were used whenever possible. This made it possible to put together a system quickly for significantly less cost.

System Design

The MATrIS design hardware consists of:

- main narrow FOV optical telescope (300-inch and 150-inch focal length configurations)
- optical platform to accept a variety of medium-sized optics (mission-specific)
- wide FOV zoom-capable finder/tracking telescope
- gimbal mounting platform
- optical tracker
- GPS tracker
- gimbal/tracker interface
- analog and digital recording systems

System Description

Optics

12.5-inch aperture main telescope

A narrow FOV telescope based on the ISAFE results was designed for reentry vehicle imaging. The telescope, shown in figures 7 and 8, is a Cassegrain focus configuration with a 12.5-inch (31.75 cm) main mirror. It has two separate secondary mirrors that enable configuration as a 300-inch (762 cm) focal length f/24 system or a 150-inch (381 cm) focal length f/12 system. The optics are designed to operate from the visible spectrum down to long wave infrared (LWIR) (~12μ). A beam splitter allows simultaneous collection of IR and visible spectra data. The f/24 system is only suitable for targets with high irradiance and slow angular rates since the relative aperture is so small that the cameras require a very long integration time to compensate for the low light levels. The telescope is currently equipped with a Raytheon (Raytheon Company, Waltham, Massachusetts) Radiance HS mid-wave IR camera and a PULNiX (JAI PULNiX, Incorporated, Sunnyvale, California) TM-745i visible light camera. The Radiance is capable of outputting images in a 12-bit digital format and an 8-bit analog format. The telescope is built within a sealed enclosure for protection in inclement weather.

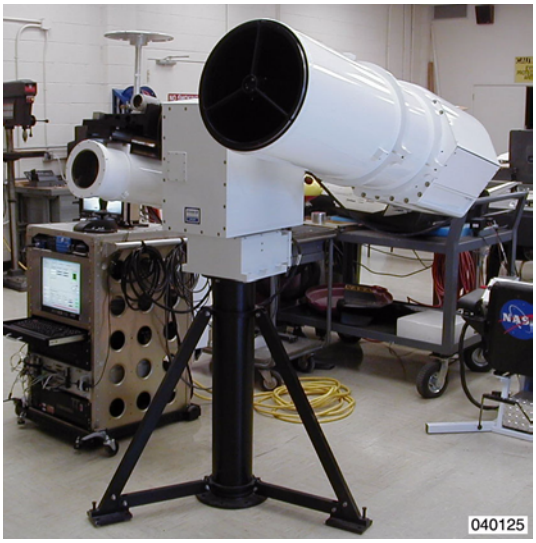

Figure 7. Narrow field of view telescope, 12.5 in.

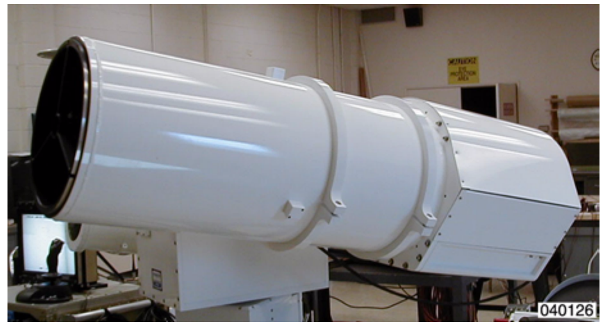

Figure 8. Side view of 12.5-inch aperture telescope.

High-zoom-capable tracking telescope

A high-zoom-capable tracking telescope is used for initial target acquisition and tracking. This telescope is a version of the PVP Advanced EO Systems (PVPAEO) (Orange, California) TH-2 system and is shown in figure 9. The tracking scope uses a Cosmicar Pentax (Pentax CCTV Lens Division, Golden, Colorado) 55x zoom with 2x extender with a PULNiX TMC-745i high-contrast black and white camera. The TMC-745i has sensitivity in the near IR also (to ~1μ). The TH-2 is mounted in a sealed enclosure for protection against the elements.

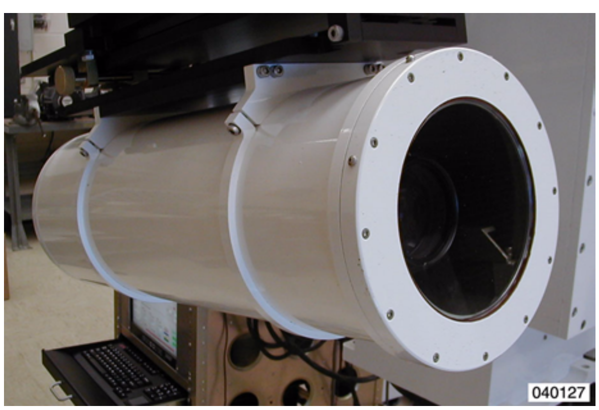

Figure 9. High-zoom-capable tracking telescope.

Other Optics

MATrIS can be configured with other optics as necessary to meet mission requirements. A CMC Electronics (CMC Electronics, Cincinnati, Ohio) Night Falcon II demonstration unit, shown in figure 10, was installed to image low- to mid-altitude fast-moving aircraft. The Night Falcon II is an MWIR telescope that was designed for long-range surveillance and reconnaissance. Like the other units, the Night Falcon II is sealed in a weather-resistant enclosure.

(a) Telescope with control box.

(b) Telescope mounted on MVSP mount.

Figure 10. CMC Night Falcon II IR telescope as tested on MATrIS.

Hardware

The gimbal mount is a PVPAEO MVSP (motorized video surveillance platform) and is shown in figure 11. The MVSP is designed with the following control, rates and accelerations: azimuth velocity from < 0.1 to 100 deg/sec, elevation velocity from < 0.1 to 60 deg/sec, azimuth acceleration to 100 deg/sec^2, elevation acceleration to 60 deg/sec^2, and microstep position control with four-microradian step resolution. The MVSP is built in an outdoor/marine-capable sealed enclosure with a temperature range from –4 to +140 °F. The MVSP for this application has been modified to be capable of going through 180° elevation (horizon to horizon) without dumping (180° azimuth change at 90° elevation).

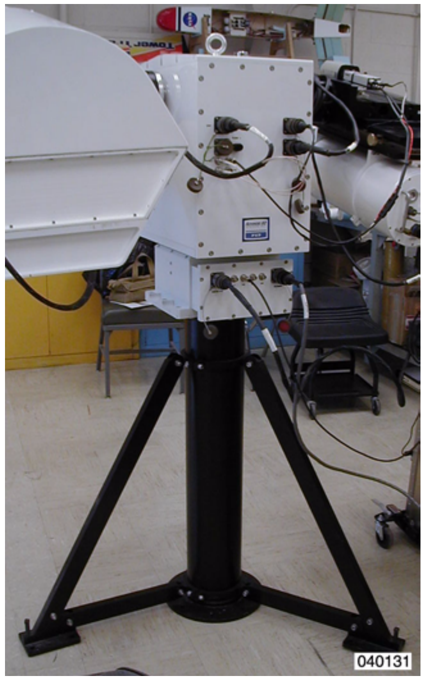

Figure 11. PVPAEO MVSP gimbal platform on tripod.

Electronics

A portable rack with all the associated electronics to run MATrIS is shown in figure 12. The main gimbal controller is a Xycom (Xycom Automation, Saline, Michigan) XVME-653 computer running Windows 2000 (Microsoft Corporation, Redmond, Washington) on a VME chassis. An optical tracker, DBA (DBA now Systems and Imagery Division, Titan Corporation, San Diego, California) Titan model 6004, is located on the same VME chassis. An Ashtech Z-Xtreme (Thales Navigation, Alexandria, Virginia) GPS receiver provides detailed coordinates and time for the imager site. A Pacific Crest (Pacific Crest Corporation, Santa Clara, California) modem receives GPS data from targets that retransmit this data, allowing differential GPS tracking capability. The 12-bit digital IR camera data is passed by way of a high-speed serial data format through the slip rings in the MVSP to a serial-to-parallel converter and stored using a PC-based digital recorder. The PC-based digital recorder was a unit developed for recording digital IR data on airborne platforms. The hardware for the unit was developed by PVPAEO, and the software by Advanced Digital Vision, Incorporated (Natick, Massachusetts). Analog video, also passed through slip rings on the MVSP, is recorded on S-VHS or Hi-8 format. Ruggedized daylight-readable LCD monitors are used to monitor the computer and video output.

Figure 12. MATRIS electronics rack.

Software

The gimbal control employs a Windows 2000-based controller that interfaces with the optical tracker, GPS tracking, or manual tracking. GPS and modem data are passed to the Xycom control computer and are processed to provide azimuth and elevation coordinates that are passed to the gimbal controller. The digital recording computer was originally designed for airborne digital data recording of onboard IR, and as such is designed to be standalone and semi-autonomous with minimal operator interaction. A steady light indicates it is ready to accept data. A toggle switch signals it to record data and the steady light changes to flashing to indicate that the unit is successfully recording. This frees a display screen and simplifies procedures for the operator.

RESULTS AND DISCUSSION

Optics

To obtain the highest spatial resolution available with the given 12.5-inch (31.75 cm) aperture, initially a 300-inch (762 cm) focal length was chosen. A secondary finder scope would be used for initial target acquisition and much of the tracking, alleviating one concern of the very narrow FOV with such a long focal length. The 300-inch (762 cm) focal length f/24 system operated well in a laboratory setup, but failed to perform adequately outside with similarly illuminated objects as would be required to image. This was due to the poor light-gathering ability of such a high f/number system. Relative aperture (RA) is a measure of the irradiation in the image of distant objects. If both the object and the image are in air (same index of refraction) then:

$$RA = \sin\Theta' \ (\Theta' = \text{exit angle}) \tag{1}$$

or

$$RA \sim 1/2N \ (\text{where } N = \text{f/number}) \tag{2}$$

So, for a given optical system and object, the intensity of the image is a function of the f/number (ref. 6). Without very bright, high-contrast targets a very long integration time is necessary with the sensor. The integration time necessary is precluded by the inability of the tracker to hold still a target with any appreciable angular rate in the very narrow FOV. The apparent motion of these targets and long integration times causes an unacceptable blurring of the image. The requirement to image targets of lower intensity and/or faster angular rates necessitates a shorter focal length system. An alternate secondary mirror configuration was designed that reduces the focal length to 150 inches (381 cm) and f/12. This increases the light-gathering ability and will reduce the motion-based blur of faster moving targets. The 12.5-inch (31.75 cm) telescope used during the ISAFE program was also dual-configured as a 300-inch (762 cm) f/24 and a 150-inch (381 cm) f/12 system.

The finder scope (a modified PVPAEO TH-2) is used for target acquisition and most of the optical tracking tasks. The ability to rapidly move between a wide FOV (acquisition) and narrow FOV (tracking) is necessary to successfully acquire and smoothly track targets.

Targets other than reentry vehicles will likely require different optics to meet individual requirements. For image acquisition of aircraft at much closer ranges and higher angular rates than those of reentry vehicles, a wider FOV system is preferred. Also, the ability to vary FOV is desirable since some types of targets tend to vary apparent size significantly during a tracking task. A CMC Night Falcon II demonstration unit was made available for evaluation of tracking and imaging aircraft at medium to long range (still much closer than reentry targets). This unit has several features that make it ideal for this application. The Night Falcon II is MWIR sensitive (InSb sensor) with a similar size focal plane array (256 x 256 array, 30μ pitch) to that of the Radiance HS used in the large telescope. Sample images from the CMC unit are shown in figures 13 and 14.

Figure 13. IR image of commercial aircraft at 15.5 miles (25 km) with CMC Night Falcon II.

Figure 14. IR image of helicopter at close range with CMC Night Falcon II.

Tracking

Tracking is accomplished either by way of an optical tracker or by providing the control program azimuth and elevation coordinates. MATrIS currently uses differential GPS in addition to optical tracking. A GPS located on the system combined with radiated GPS data from targets can provide a very accurate means of tracking. The information from both GPSs is processed by a MATLAB (The Math Works, Natick, Massachusetts) program to obtain relative azimuth and elevation to the target and is sent to the gimbal control. GPS tracking has the ability to be very accurate but delays and dropouts can cause tracking errors. The data delays and dropouts in the GPS tracking require extrapolation of the target velocity vector, which can cause problems with tracking aggressively-maneuvering vehicles. GPS coordinates and pre-programmed or other knowledge of the trajectory is almost a necessity for initial acquisition of many targets. Optical tracking is not as inherently accurate, can be jittery, and can loose-lock on the target if another object enters the field (for example, clouds). Optical tracking does not offer any benefit for initial target acquisition. The ability to blend optical and GPS tracking offers a possible method to overcome many of the combined limitations and is being pursued.

CONCLUDING REMARKS

A mobile, rapidly deployable ground-based system has been developed to track and image targets of aeronautical interest. The MATrIS (Mobile Aerial Tracking and Imaging System) was conceived through a study of ground-based imaging to obtain global aerothermal characteristics of reusable launch vehicles (RLVs). This study was conducted jointly with NASA and the Missile Defense Agency/Innovative Science and Technology Experimentation Facility (MDA/ISTEF). The favorable results indicated the desire to have a relatively inexpensive, mobile, and rapidly deployable system to obtain these measurements. Further, such a system can be adapted for use with other aeronautical targets in addition to reentry vehicles.

Many challenges in developing this system persist. Although high spatial resolution is desired the resultant long-focal-length, high-f/number systems require very precise tracking because of the high sensor integration time necessary for the small relative aperture and the narrow field of view. Larger optics and more precise trackers were cost prohibitive, so shorter focal length systems are necessary for imaging lower contrast, fast angular rate targets. Acquiring, and more so re-acquiring, a target is extremely difficult without near-real-time trajectory data (known trajectory, GPS or radar). GPS tracking and optical tracking each have benefits and limitations. Blended GPS and optical tracking may alleviate many of these limitations and is being pursued.

Future plans include demonstrating this system on the next practical reentry event and expanding the range of vehicles and flows that can be visualized with long range IR thermography.

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13. ABSTRACT (Maximum 200 words)

A mobile, rapidly deployable ground-based system to track and image targets of aeronautical interest has been developed. Targets include reentering reusable launch vehicles as well as atmospheric and transatmospheric vehicles. The optics were designed to image targets in the visible and infrared wavelengths. To minimize acquisition cost and development time, the system uses commercially available hardware and software where possible. The conception and initial funding of this system originated with a study of ground-based imaging of global aerothermal characteristics of reusable launch vehicle configurations. During that study the National Aeronautics and Space Administration teamed with the Missile Defense Agency/Innovative Science and Technology Experimentation Facility to test techniques and analysis on two Space Shuttle flights.

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